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Evaluation of the thermal stability of a low-coherence interferometer for precision surface profilometry

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ABSTRACT

Manufacturing of precise structures in MEMS, semiconductors, optics and other fields requires high standards in manufacturing and quality control. Appropriate surface topography measurement technologies should therefore deliver nm accuracy in the axial dimension under typical industrial conditions.
This work shows the characterization of a dispersion-encoded low-coherence interferometer for the purpose of fast and robust surface topography measurements. The key component of the interferometer is an element with known dispersion. This dispersive element delivers a controlled phase variation in relation to the surface height variation which can be detected in the spectral domain.
A laboratory setup equipped with a broadband light source (200 - 1100 nm) was established. Experiments have been carried out on a silicon-based standard with height steps of 100 nm under different thermal conditions such as 293.15 K and 303.15 K. Additionally, the stability of the setup was studied over periods of 5 hours (with constant temperature) and 15 hours (with linear increasing temperature). The analyzed data showed that a height measurement of $97.99 \pm 4.9nm$ for 293.15 K and of $101.43 \pm 3.3nm$ for 303.15 K was possible. The time-resolved measurements revealed that the developed setup is highly stable against small thermal fluctuations and shows a linear behaviour under increasing thermal load. Calibration data for the mathmatical corrections under different thermal conditions was obtained.

Keywords: optical metrology, interferometric measurement, dispersion based measurements, in-line characterization, low-coherence interferometry, surface profilometry, stability

1. INTRODUCTION

The characterization of technical surfaces is increasingly important [1]. Industry branches like semiconductors, MEMS and photonics as well as fields of research like biomedicine rely on the functionalization of surfaces, [2–8]. The constant monitoring of surface features such as height, roughness or texture during different processing steps is an important part of quality assurance, [9, 10]. Tools which should be used in-line have to fullfill different requirements in distinction to classical lab-based surface profiling technologies. First of all, the measurement speed has to be aligned with the respective processing step. Second, the measurement has to be performed autonomously for a large variety of samples. As the amount of data gathered is often large, appropriate algorithms have to monitor key values constantly and only report on deviations. Last but most important, tools for inline operation have to be robust against the environmental influences they are operated in, [11]. These can be for example, of thermal, vibrational or electro-magnetical nature.
Common metrology approaches such as confocal laser scanning microscopy [12] and scanning white-light interferometry [13] have shown the appropriate accuracy for industrial surface profilometry. Though these technologies

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deliver a good performance on a lab-scale with appropriate test samples, they are not applicable to situations in a production environment with more complex samples due to speed issues, [9].Another common measurement technology for surface profiling is so called scatterometry which retrieves surface profile information based on reflected intensities, [14–16]. The technique relies on the reflection on periodic surface structures where a well-known model of the materials and the structures involved enable nm-precise measurements, [17, 18]. These requirements limit its flexibility and the use as an in-line tool. Furthermore, technologies such as atomic force microscopy (AFM) perform well in terms of axial and lateral resolution, [19]. They have been shown to be excellent tools in laboratory environments for applications such as microbiology and nano-structured materials [20–22]. However, AFM measurements over areas larger than a few μm^2 require special installations and measurement times increase significantly, [23].
Due to the complexity of operation, the stability of common approaches is not suitable for installations as a process accompanying tool. The aim of this work is to qualify a dispersion-encoded approach to low coherence interferometry with nm height resolution in terms of its mechanical an thermal stability.

2. EXPERIMENTAL APPROACH

The examination of surface profiles with nm resolution in the height dimension in in-line situations has been shown using dispersion-encoded low-cohernce interferometry, [24]. The typical configuration of such a setup consists of a broadband light source, a reference section with controlled dispersion properties as well as a sample section and an imaging spectrometer for signal detection, Fig. 1.

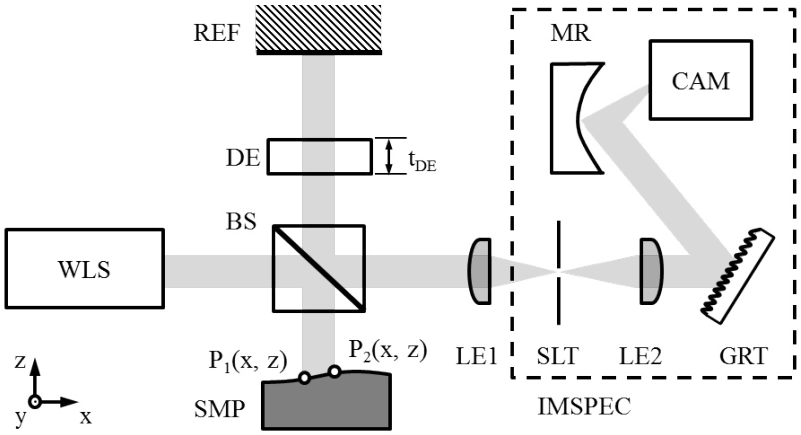


Figure 1. Experimental setup with WLS - white-light source, BS - beam splitter, SMP - sample where $P_1(x, z)$ and $P_2(x, z)$ are two different points with a height z on line in x-direction, REF - fixed reference mirror, DE - dispersive element with the thickness t_{DE}, LE1 - lens to image the sample onto the SLT - slit of the IMSPEC - imaging spectrometer where the image of the slit is transported and spectrally decomposed by LE2 - collimating lens, GRT - grating as well as LE3 - imaging lens to CAM - camera where the spectral information for every point on the line in x-dimension is recorded

The setup is illuminated by a white light source (EQ-99X, Energetiq Technology, Inc., USA) which is split into a reference and a sample arm using a 50/50 cube beamsplitter. The dispersion is is controlled by a bulk glass substrate (Schott N-BK7, $t_{DE} = 2mm$) in the reference section. The detection of the recombined light of reference and sample section is done using an appropriatly designed imaging spectrometer in a spectral range between $500 - 800nm$. After data acquisition, the gathered spectral information is proecessed with an in-house developed algorithm which implements proper wavelength calibration, filtering and the calculation of surface height profiles.
The detection in the spectral domain reveals a distinct phase minimum for a certain wavelength, the so called equalization wavelength λ_{eq}, for which the arm lengths are equal. The shape of the spectrum as well as the position of the phase minimum can be controlled by the amount of dispersion present in the reference section.

This can be described by using the equations:

$$I(\lambda, x) = I_0(\lambda) \cdot (1 + \cos \phi(\lambda, x)) \tag{1}$$

$$\phi(\lambda, x) = 2\pi \frac{(n(\lambda) - 1)t_{DE} - \delta(x)}{\lambda} \tag{2}$$

As the position of the phase minimum is also dependent on the difference between the reference and sample section, it can be utilized as a measure for the height of a surface, Fig. 2.

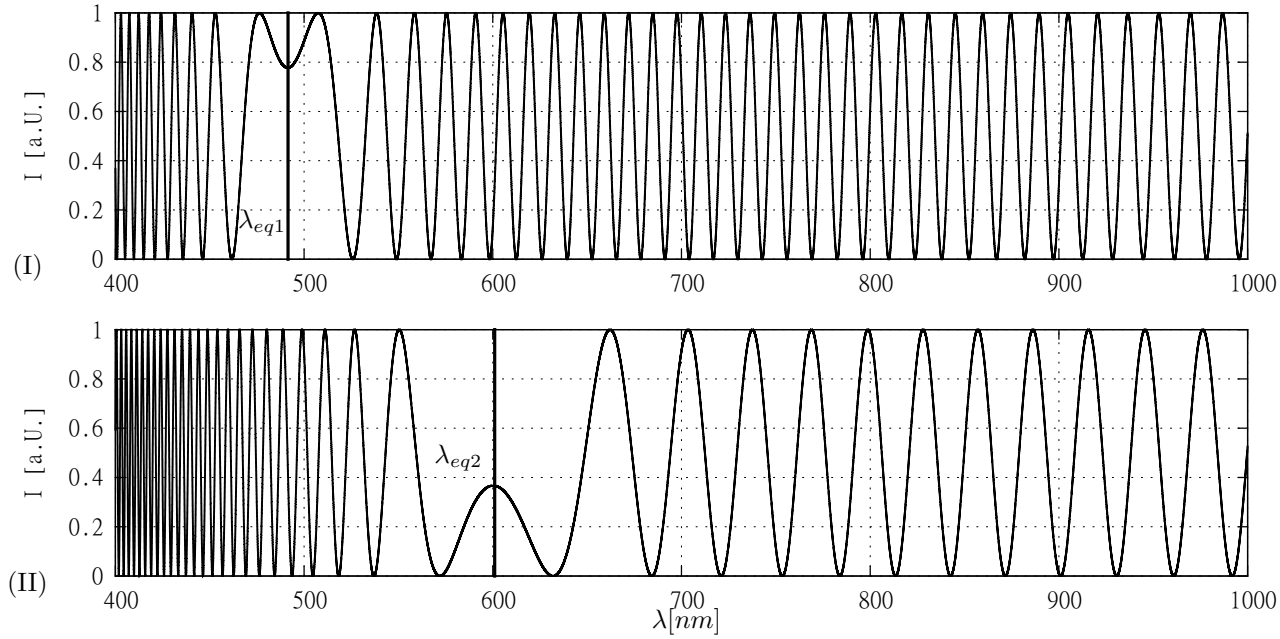


Figure 2. Schematic representation of intensity signals at the points $P_1(x, z)$ and $P_2(x, z)$ (denoted with I-II) where the samples surface with independent heights (e.g. z_1 and z_2) leads to different equalization wavelengths λ_{eq1} and λ_{eq2}

By using materials with an appropriate thickness t_{DE} in combination with its distinct refractive index $n_{group}(\lambda)$ a certain measurement range Δz and resolution can be tuned:

$$\Delta z(\lambda) = n_{group}(\lambda) \cdot (t_{DE}/2) \tag{3}$$

Within this work, the stability of the setup described above especially in the context of thermal influences, is studied. In a initial experiment, the accuracy of the setup is investigated by measuring the surface profile of a Si-based height standard with a step height of 100 nm (Simetrics VS, Simetrics GmbH, Germany) at a room temperature of 293.15 K. For this purpose, the sample was mechanically re-positioned 10 times. Furthermore, the same experiment is repeated after increasing the temperature about 10 K in the same fashion. A second experiment is conducted by measuring the same height step at 293.15 K for a period of 5 hours while the temperature is kept constant and monitored. This experiment is intended to monitor how small fluctuations of temperarature influence the signal. Afterwards, a third experiment is used to measure the step height while increasing the temperature gradually. Starting at a temperature of 293.15 K, the temperature is increased over a period of 15 hours with a rate of 0.66 K/h.

3. RESULTS

The purpose of the first experiment was to determine the stability of the setup and the positioning system in two differrent thermal states. It is obvious that the height of the standard could be measured very preciscley in both cases, Fig. 3.

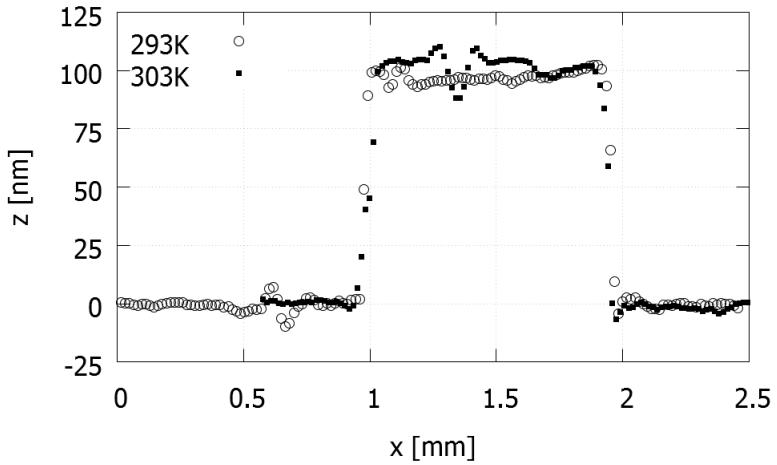


Figure 3. Results of the height profile measurements of the 100 nm step at temperatures of 293.15K and 303.15K respectively, whereas the sample was moved mechanically for 10 repetitive measurements

In case of the 293.15K measurement, both edges of the step could be determinded with a standard deviation of 5.4 and 4.9 nm at heights of 97.99 and 97.72 nm respectively. In comparison, the same step was measured on both edges with heights of 101.43 and 101.44 nm and respective standard deviations of 3.3 and 3.6 nm for a temperature of 303.15K. The slightly higher measured step height can not be explained by a pure thermal expansion of the silicon step standard but is a combined effect of all components of the setup. The behaviour of the setup is therefore examined in a separate experiment. It should be noted, that the standard deviation of the height between the individual measurements at 303.15K is lower than at 293.15K. It can be seen in the plot that, both measurements show artifacts on parts where the sample is considered to be plain. One example can be seen in the 303.15K measurement at an x-position of 1.3 mm. The origin of these artefacts could be found by analysing the raw data as an effect of the spectrometer slit on the image quality . A proper hardware improvement or mathematical compensation has to be worked out in future developments. The artifacts occure at different postions for the two different measurements because the sample was not measured at the same position for every termperature.
In case of the 5 hour measurement of the step at 293.15K a high stability of the profile measurement could be achieved, Fig. 4 a).

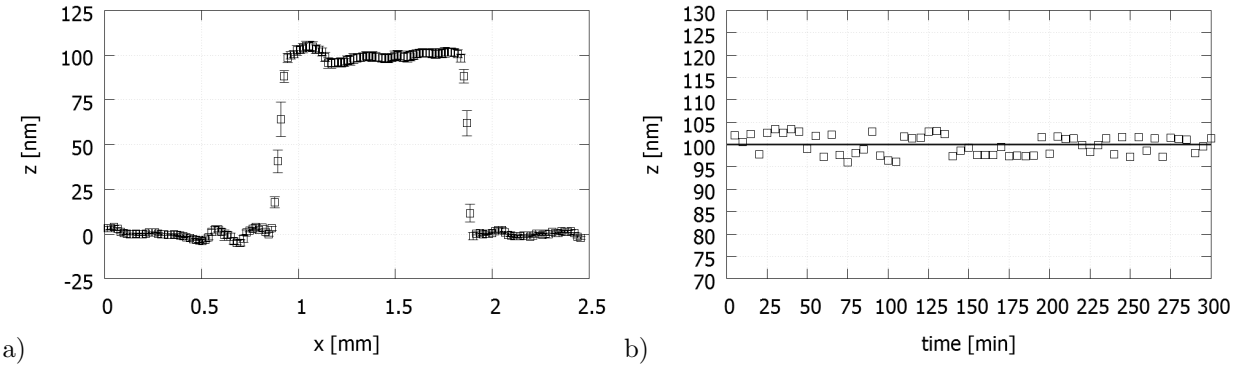
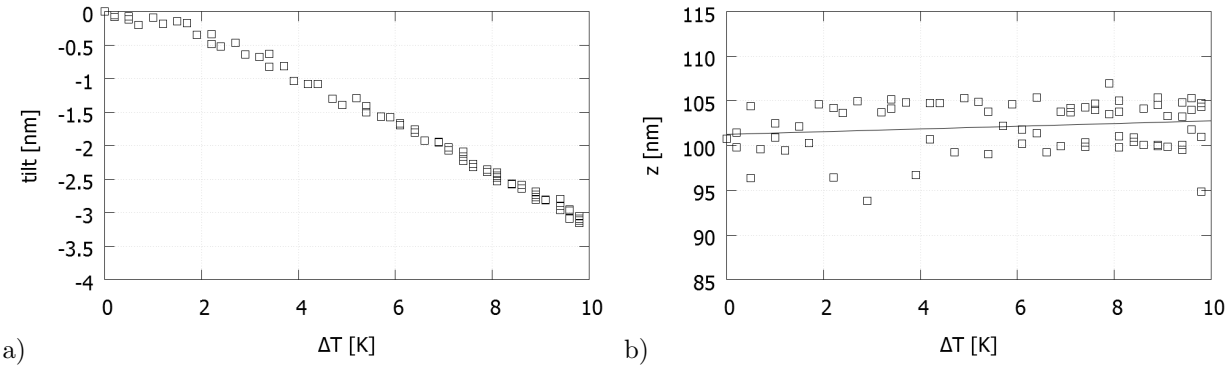


Figure 4. Results of the 5h experiment with a) mean heigh profile including corresponding errorbars for measurements every 5 minutes and b) calculated height values for the left edge over the measurement time of 5 hours

The measured heights of both edges were 99.98 and 99.89 nm with standard deviations of 2.2 nm respectively. Apart from the data at the edges the errorbars prove a very stable measurement over a long period of time.

When analysing the determined height of one of the edges over time, it is clear that no significant change in height was measureble, Fig. 4 b). A linear regression revealed a slope of only $-0.002nm/min$.
In contrast, the measurement of the height under increasing temperature shows a measurable slope, Fig. 5 a).



a) b)

Figure 5. Result of the experiment at a linear temperature increase if 0.66 K/h over 15 h with a) the tilt of the sample in relation to the reference mirror over the temperature change and b) the calculated height values for the left edge over the temperature change showing a slope of 0.15 nm/K

A linear regression revealed that the measured height increased at a rate of 0.15 nm/K during the 15 hour measurement. The standard deviation of the meausred height stayed constant with a size of 2.6 nm. Furthermore, it could be found that a tilt of the measured height profile in relation to the reference arm mirror happended due to the temperature increase, Fig. 5 b). The tilt happened in a linear fashion at a rate of 3 nm/K.

4. CONCLUSION AND OUTLOOK

The scope of this work was the evaluation of the stability of a dispersion-encoded low-coherence interferometer. The construction of the interferometer enables a fast examination of surface height profiles along a line of a few millimeters with nm height resolution. The setup and its analyzing algorithms are implemented in a way to perform process accompanying measurements, for example, in the semiconductor industry. For the assurance of precision during operation it is especially important to know the behaviour regarding influences such as thermal load.
Therefore, the main part of this work focussed on the characterization of the measurement properties under different thermal load situations. A series of four experiments was performed with a Si-based height standard having a step height of 100 nm. In repetitive measurements, the resolution of the setup was determined by measuring the step height under static temperatures of 293.15 K and 303.15 K on both edges of a step. It could be shown, that the result of the 293.15 K measurement was $97.72 \pm 5.4nm$ and $97.99 \pm 4.9nm$ while the result of the 303.15 K measurement was $101.43 \pm 3.3nm$ and $101.44 \pm 3.6nm$. In a different experiment, the height of the standard was constantly measured over a period of 5 hours. It could be shown, that the uncertainty of the measurement fluctated about 2.2 nm while the temperature was kept constant in the same period of time. The measured height of 99.98 and 99.89 nm on both edges is in good agreement with the nominal height of 100 nm. The environmental conditions were similar to common conditions in a cleanroom. In order to investigate the temperature dependency of the setup even further, a long term measurement with increasing temperature was conducted. Over a period of 15 hours the temperature was increased with a 0.66 K/h rate while the step height was measured. It could be shown, that the relative measured step height of the standard fluctated in the same size as in previous experiments while an absolute drift of about 0.15 nm/K could be recognized. The temperature dependency showed a linear trend. Additionally to the absolute difference in the height measurement, a de-adjustement of the setup became visible which led to a slight tilt of the sample data of 0.3 nm/K. This data was saved as reference and could be used to mathematically correct for the tilt of the measured data.
The experiments have shown that the proposed low-coherence interferometer only displays a minor temperature dependence. In particular, small fluctuations can be compensated by averaging of data, while larger deviations

due temperature drifts larger than $1K$ can be corrected using an appropriate caibration data provided with these experiments.

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